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ANALYSIS OF COMPUTED FLOW PARAMETERS FOR A SET OF SUDDEN STALLS IN LOW-SPEED TWO-DIMENSIONAL FLOW

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SUMMARY

This note presents an analysis from which it is inferred that there are two distinct mechanisms of nose stall in low-speed two-dimensional flow. These are presumed to be the two hypothetical mechanisms already described in the literature, mechanisms which may be termed "bubble-bursting" and "reseparation." A basis for distinguishing between the two mechanisms is provided by a criterion for transitional reattachment of a separated laminar boundary layer (i.e., for formation of a laminar-separation bubble), proposed independently by Tani, and by Owen and Klanfer, and indicated here to be essentially valid.

The analysis considers a set of sudden airfoil stalls obtained under fixed test conditions. Theoretical velocity distributions about the leading edges just prior to stall are computed. For those stalls ascribed to the reseparation mechanism, a correlation is demonstrated between high velocity peaks and either steep initial adverse gradients or thin boundary layers in the region of these gradients. The correlation is shown not to apply to stalls ascribed to bubble-bursting. This correlation was anticipated by a simple argument, set forth in the text, and the conclusions above are based on the work performed in verifying the correlation. Possible applications are not considered.

INTRODUCTION

The three types of airfoil stall described by McCullough and Gault in reference 1 have now become very familiar. These three types were distinguished as follows: a gradual spreading forward, as $c_{l_{max}}$ is approached, of separation initiated at or near the trailing edge (trailing-edge stall); a sudden appearance, at $c_{l_{max}}$, of extensive separation from the vicinity of the leading edge (leading-edge stall); and a gradual spreading rearward, as $c_{l_{max}}$ is approached, of separation initiated at or near the leading edge (thin-airfoil stall). However, for airfoils with round leading edges, the onset of the rearward-spreading separation characterizing the third type of stall is sudden, and has been treated as the same phenomenon as occurs at maximum lift in the second type of stall. To this phenomenon the term "nose stall" has sometimes been applied (as in ref. 2) and will be adopted here.

The flow changes associated with nose stall are the subject of this paper. Two distinct hypotheses have been advanced concerning these flow changes, each hypothesis supported by indirect experimental evidence. (This evidence is briefly reviewed in the appendix.) Before citing the hypotheses specifically, certain preliminary remarks may be in order.

Both hypotheses consider nose stall to be strictly a leading-edge flow phenomenon (independent of boundary-layer conditions far downstream), and both consider the phenomenon to be closely associated with the laminar-separation bubble that has come to be considered a standard feature of otherwise attached flow about a highly loaded leading edge. On the basis of the first assumption, it is legitimate to consider the leading-edge region by itself, without reference to downstream geometry or flow conditions, or to the manner in which the aerodynamic loading of the leading edge is varied. With regard to the laminar-separation bubble, it is well to recall that this distinctive region of separated flow has been studied in some detail, notably by Gault in reference 3. Its characteristic feature is the beginning of transition close to the point of reattachment, and its extent is so short as to have no significant effect on aerodynamic loading. In this paper, the presence of the bubble is assumed as an antecedent to nose stall.

The first hypothetical mechanism of nose stall consists of the sudden failure of the detached boundary layer downstream of laminar separation to reattach to the surface in the short distance characteristic of the laminar-separation bubble. This "bursting of the bubble" has been described by McCullough and Gault and has been widely accepted as the most probable mechanism of nose stall. The second mechanism consists of the sudden reseparation of the boundary layer a short distance downstream of the bubble. This mechanism was first postulated as the general mechanism of nose stall, "with the exception of low Reynolds numbers," by Wallis in reference 2.

As these two mechanisms were considered, it became apparent that both might commonly occur. A possible means of indicating this fact was implied by a certain line of reasoning concerning the reseparation mechanism. Specifically, it was reasoned that it might be possible to correlate certain leading-edge flow parameters at stall, for stalls by this mechanism only. The correlation would not be expected for stalls due to bubble-bursting. Thus, if the two mechanisms could be distinguished on the basis of some objective criterion, and if the anticipated correlation could be demonstrated for a set of stalls attributed to one, but not for a set attributed to the other, the probable validity of both mechanisms would be supported.

The analysis which follows begins with the physical argument by which the correlation of flow parameters was anticipated. The various assumptions, criteria, and methods necessary to the clear establishment of the correlation are then discussed in some detail, with major emphasis on the logical use of a criterion for attributing particular stalls to the reseparation mechanism. Finally, the correlation is demonstrated and discussed, and its nonvalidity for bubble-bursting stalls is indicated.

The flow parameters are based on velocity distributions computed by an exact theory. For programing and carrying out most of these difficult computations, the authors are indebted to Yvonne Settle. In a few cases, detailed computations performed at the Langley Research Center were utilized.

NOTATION

C_p	pressure coefficient
C_Q	area-suction flow coefficient
c	airfoil chord
c_l	lift coefficient
Δc_l	increment in lift coefficient
H	boundary-layer shape parameter, $\frac{\delta^*}{\theta}$
L	characteristic model length
M	Mach number
R_c	chord Reynolds number, $\frac{U_\infty c}{\nu}$
$R_{(\delta)}$	$\frac{U(\delta)}{\nu}$
R_θ	$\frac{U\theta}{\nu}$
s	distance along a surface from a stagnation point, unless otherwise specified
Δs_l	approximate adverse laminar run, defined in sketch (c)
U	theoretical velocity in incompressible potential flow
x	chordwise distance, from the leading edge

α	angle of attack
$\Delta\alpha$	increment in angle of attack
(δ)	arbitrarily defined boundary-layer thickness
δ^*	boundary-layer displacement thickness
θ	boundary-layer momentum thickness
ν	kinematic viscosity

Subscripts

max	maximum
min	minimum
P	peak
S	at or near laminar separation
∞	free stream

ANALYSIS

Argument

The question which originally prompted this investigation was: what determines the limiting value of the minimum pressure coefficient near the leading edge of an airfoil when stall is due to turbulent separation? From this very general statement, the question was narrowed down to: what determines the limiting value of $C_{p_{min}}$ for nose stall by the reseparation mechanism under a fixed set of test conditions? As a possible answer to either question, but a particularly plausible one to the more specific question, a basic notion was conceived. This notion was that the imminence of turbulent separation should depend upon the initial thickness of the reattached boundary layer just downstream of the laminar-separation bubble, being less likely for a thin than for a thick boundary layer because of turbulent mixing. It was argued that the thickness of this reattached layer should, in turn, depend upon the thickness of the laminar boundary layer at its point of separation, and the latter thickness should depend upon the length of the adverse laminar run from the point of minimum pressure to the separation point. Finally, the length of the adverse laminar run should depend upon the steepness of the adverse pressure gradient in the region of that run, being shorter for a steeper gradient. In sum, it was anticipated that a correlation should exist (for cases of nose stall by the reseparation mechanism under a given set of test conditions) between the value of $C_{p_{min}}$ at stall and some systematic measure of the initial adverse pressure gradient, also at stall.

The argument above ignores at least two important factors. The first is the effect of the history of the boundary layer upstream of minimum pressure on its thickness at laminar separation. The second is the tendency of a relatively steep adverse pressure gradient to promote separation of any type, a tendency that would counteract the presumably favorable effect on turbulent-boundary-layer thickness. Nevertheless, the correlation was conceived as a distinct possibility, and the work entailed in investigating this possibility was undertaken. For reasons discussed later, a similar correlation would not be expected for nose stalls due to bubble-bursting.

Basis of the Correlation

Criterion for attributing a sudden stall to the reseparation mechanism.- As noted, the distinguishing feature of a laminar-separation bubble is the beginning of transition close to the point of reattachment. This feature alone constitutes strong evidence for the generally accepted hypothesis that the turbulent mixing resulting from transition is the primary cause of reattachment. An extension of Chapman's terminology (ref. 4), under which the bubble flows considered here would be termed "transitional" rather than "laminar," suggests the term "transitional reattachment" for this process.

In terms of transitional reattachment, bubble-bursting is the sudden failure of such reattachment to occur, and reseparation is the sudden separation of the boundary layer downstream of such reattachment. Therefore, the two presumed mechanisms of nose stall should be distinguishable on the bases of a criterion for the occurrence of transitional reattachment.

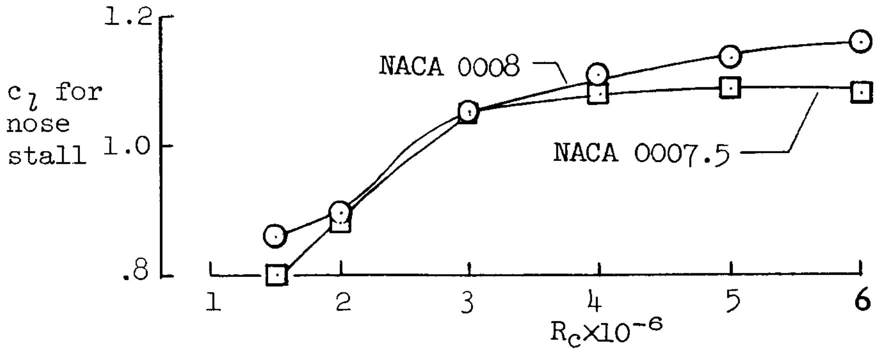
Such a criterion was first suggested by Tani (ref. 5) and later, independently, by Owen and Klanfer (ref. 6). Since the validity of the criterion has been in doubt, it is appropriate to review its origins, and the objection that has been raised to it.

The criterion is the boundary-layer Reynolds number at laminar separation, $R_{(\delta)_S}$. (This Reynolds number is defined by the local outer velocity and boundary-layer thickness. Tani used momentum thickness, Owen and Klanfer displacement thickness; others have used physical thickness, as in references 7 and 3. The symbol (δ) is used here to indicate an arbitrary but unspecified choice among these three thicknesses.) The criterion is thought of as an indicator of the imminence of transition in the separated flow, and therefore of the likelihood of transitional reattachment. It was argued initially that there ought to be a unique value (or narrow band of values) of $R(\delta)_S$ above which transitional reattachment occurred, and below which it did not. Since all nose stalls were thought, at the time, to be due to bubble-bursting, there was the implicit idea in this notion that $R(\delta)_S$ decreases with increasing loading, being above the critical value when the laminar-separation bubble first formed, and dropping to the critical value at nose stall.

The objection that has been raised is simply that nose stalls have been observed for values of $R(\delta)_S$ far above the presumed critical (refs. 3 and 8). This objection depends, of course, on the assumption that these stalls were due to bubble-bursting. When the possibility of reseparation is taken into account, the objection loses its basis.

Another objection to the adequacy of the $R(\delta)_S$ criterion, for valid cases of bubble-bursting, can be offered. This is that $R(\delta)_S$ appears to be approximately constant with increasing loading, on the basis of both physical measurements (ref. 3) and theoretical calculations (refs. 6, 8, and 9). In other words, the implicit idea of decreasing $R(\delta)_S$ as stall is approached does not seem to be borne out. The possibility remains, however, that the phenomenon of bubble-bursting is restricted to a certain range of values of $R(\delta)_S$, and never occurs for values above that range. This would mean that the Tani-Owen criterion still retained an essential validity.

In seeking an alternative to this criterion, Crabtree has suggested in references 8 and 10 the plausible idea that bubble-bursting occurs when the abrupt pressure rise, characteristic of transitional reattachment, exceeds a certain critical value expressed in suitable dimensionless form. (For discussions of this characteristic pressure rise, see refs. 3 and 4.) He points out that an increase in $R(\delta)_S$ will move transition forward, reducing the transitional pressure rise for a given gross loading, and thus permitting a higher loading before the bubble bursts. Such an increase in $R(\delta)_S$ would result, for example, from an increase of over-all Reynolds number. Therefore, the aerodynamic loading for nose stall by bubble-bursting should increase with Reynolds number (as is sometimes observed). Furthermore, if all nose stalls were due to bubble-bursting, regardless of the value of $R(\delta)_S$, this trend should continue until transition moved ahead of the point where laminar separation would otherwise occur. An indication that this does not seem to be the case is provided by the curves of sketch (a), taken from McCullough's investigation of certain moderately thin airfoils (ref. 11). These curves suggest the interpretation that nose stall at Reynolds numbers below about 3×10^6 was due to bubble-bursting but at higher Reynolds numbers was due to some other mechanism. In other words, the curves are in accord with the suggestion of the last paragraph, that bubble-bursting is restricted to a certain range of values of $R(\delta)_S$ (within which Crabtree's hypothesis would apply) but fails to occur for values above that range.



Sketch (a)

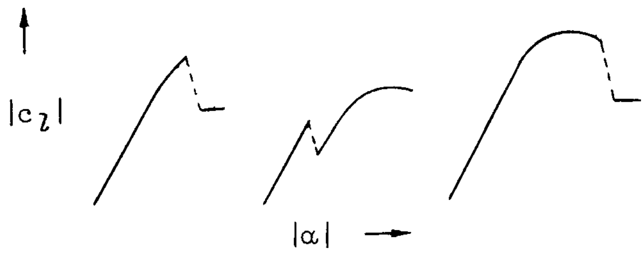
Based on the foregoing, the view is adopted here that, for a given set of test conditions (1) there is a critical value of $R_{(\delta)_S}$ above which all nose stalls are due to reseparation; (2) below this value there is a range in which nose stalls may be due to either supposed mechanism; and (3) for still lower values, all nose stalls are due to bubble-bursting.

As will be discussed later, the correlation itself not only lends strong support to this view, but it also was considered to provide a rational basis for choosing the approximate critical value of $R_{(\delta)_S}$ for the particular data analyzed. This value was $R_{\theta_S} \approx 350$, as against Tani's suggested value of 240. Since the latter was conceived as a unique value separating reattaching from non-reattaching flows, whereas the present value is chosen as the maximum of a range within which a flow may or may not reattach, the two figures are in reasonable agreement.

Selection of sudden stalls.- Because of the scarcity of experimental pressure-distribution data, it was necessary to select probable cases of nose stall on the basis of force data alone, that is, on the basis of apparent suddenness of the stall. Accordingly, all instances of sudden stall were chosen from published lift curves obtained in standard force tests of smooth-surfaced, two-dimensional airfoil models, in the Langley low-turbulence pressure tunnel, at a Reynolds number of $(6.0 \pm 0.1) \times 10^6$, and Mach numbers never greater than 0.2 (refs. 12 to 20). Stalls due to negative as well as to positive angle of attack were used. In this regard, no distinction was made between symmetrical and cambered airfoils; that is, the two stalls were always treated independently.

To be relatively sure that the stalls were in fact sudden, the arbitrary requirement was made that the two points of data defining stall should indicate a slope $|\Delta c_l/\Delta\alpha|$ of at least one tenth per degree, with $|\Delta c_l|$ itself at least one tenth.

The stalls were chosen without regard to $c_{l_{max}}$; that is, any sudden loss of lift meeting the above requirement was regarded as a valid instance of sudden stall, whether or not it occurred at $c_{l_{max}}$; the three possibilities are illustrated in sketch (b). (Actually, no qualifying stalls were found corresponding to the second possibility.)



Sketch (b)

The criterion discussed above for distinguishing stalls due to reseparation was utilized as follows. From a theoretical velocity distribution, the quantity R_θ can be computed for any point in a laminar boundary layer by means of the formula

$$R_\theta{}^2 = \frac{0.45\ R_c}{(U/U_\infty)^4} \int_0^{s/c} \left(\frac{U}{U_\infty}\right)^5 d\left(\frac{s}{c}\right) \tag{1}$$

which follows from the equation

$$\theta^2 = 0.45\nu U^{-6} \int_0^s U^5 ds$$

given by Curle and Skan (ref. 21), as well as by earlier investigators. For leading-edge velocity distributions at high lift, it was found, on the basis of several preliminary computations, that R_θ computed in this way did not vary substantially through the region in which laminar separation could reasonably be expected to occur (i.e., the choice of separation point was not critical). Accordingly, separation was always assumed to occur where the velocity had fallen 6 percent from its peak value. The subscript S will hereafter refer to this point.

It was also found that R_{θ_S} at high lift correlated quite well with any geometric parameter indicating the general thickness or thinness of the leading edge, such as the leading-edge radius or the thickness (not the ordinate from the chord) at some forward station. It was rather interesting to find that this was true for cambered airfoils whether stall at positive or negative angle of attack was being considered; in short, R_{θ_S} was not greatly affected by camber in either direction, in any amount. This meant that a preliminary selection of airfoils could be based on leading-edge geometry alone. Ultimately, the computation of R_{θ_S} at stall was carried out for all airfoils selected.

The final selection of airfoils is summarized in table I. While the list is far from exhaustive, a deliberate attempt was made to include as wide a variety of shapes as possible, as well as a sufficient number of cases to indicate clearly the validity of the correlation.

Computation of velocity distributions.- Since the stalls were selected on the basis of force data alone, it was necessary to compute theoretical velocity (or pressure) distributions for the leading-edge flows just prior to stall. The computations were carried out by the exact method of Theodorsen for incompressible potential flow (refs. 22 and 23). In most instances, they were performed (except for one manual operation) on an automatic digital computing machine. Results of such computations were obtained in great detail in the critical leading-edge region and are considered very accurate. For a few symmetrical airfoils, new computations were not carried out; instead, through the cooperation of the Langley Research Center, theoretical parameters from original desk computations performed there were obtained and utilized.

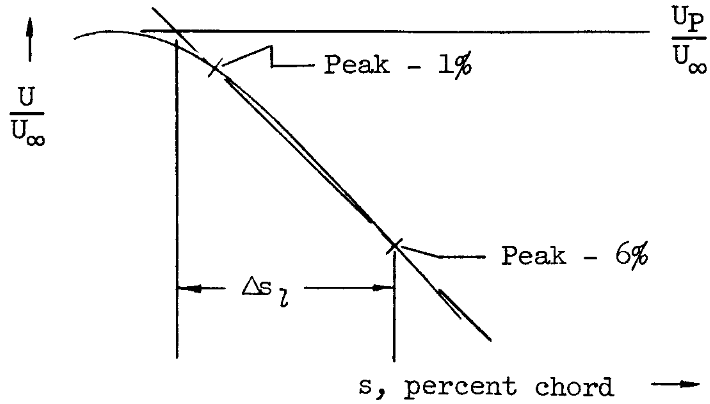
In all cases, the leading-edge velocity distribution was computed for the theoretical flow defined by both the measured lift coefficient and the measured angle of attack at stall; that is, the Kutta condition was ignored. As shown by Pinkerton (ref. 24), this procedure can be expected to yield better agreement with experiment (except near the trailing edge) than would be obtained by computation of the Kutta condition flow for either the measured c_l or the measured α.

When the increment in angle of attack between the unstalled and stalled conditions was not more than 1°, it was assumed that stall occurred at the beginning of the increment. When the increment was more than 1°, it was assumed that stall occurred at its midpoint. In the latter case, for a curve of the first type illustrated in sketch (b), stall c_l was determined by smooth extrapolation of the prestall segment of the curve; for a curve of the third type, it was taken as the measured c_l at the beginning of the increment.

It may be remarked here that the analysis has been based on velocity distributions, rather than on pressure distributions, for the simple reason that the former must be computed in any case to obtain the latter. No other reason for preferring one over the other was evident. In terms of velocity distributions, therefore, the anticipated correlation would be one of peak velocity ratio at stall, U_P/U_∞, against a systematic measure of the initial adverse velocity gradient.

The Correlation

For each velocity distribution, the initial adverse gradient was taken to be defined by the points at which the velocity had dropped 1 percent and 6 percent, respectively, from the peak value, as illustrated in sketch (c). Rather than the actual slope of the line through



Sketch (c)

these points, however, the surface distance Δs_l, defined in the sketch, was used. The subscript l indicates that the distance was thought of as a rough approximation to the adverse laminar run from peak velocity to separation point.

The plot of U_P/U_∞ vs. Δs_l for the stalls of table I is shown in figure 1. A correlation of those points for which R_{θ_S} is greater than about 350 is evident. Some of the other points also appear to correlate, but some do not. This is just the pattern to be expected from the stated assumptions that (1) the correlation should apply only to reseparation stalls, and (2) such stalls should occur consistently only when R_{θ_S} is above some critical value. In fact, these assumptions imply that figure 1 constitutes a reasonable basis for choosing the approximate critical value of R_{θ_S} for this analysis.[1]

Before proceeding further with a discussion of the correlation as it relates to the phenomenon of nose stall, it is perhaps well to point out two particular aspects of figure 1. The first is that the variation with leading-edge loading of U_P/U_∞ and Δs_l for any particular airfoil yields a curve that is much steeper than the correlation curve itself (i.e., the latter curve does define a limit beyond which the velocity peak on any given leading edge cannot rise). The second aspect which may call for comment is the magnitude of the highest velocity peaks indicated by the figure. These correspond to pressure coefficients as low as -17.5, a numerical magnitude distinctly greater than anything that has actually been measured, to the authors' knowledge, under test conditions comparable

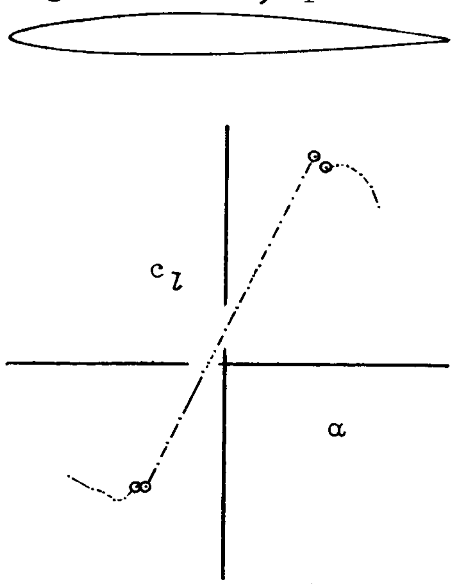
[1]The points with flagged symbols are discussed separately later.

to those pertaining to the data. Violation of the Kutta condition is probably the major cause of these unrealistically high velocity peaks, since the theoretical flow around the trailing edge results in a down load in that vicinity which must be compensated by a greater lifting load near the leading edge. Since all the velocity distributions were computed in the same way, it is to be assumed that all the peaks are higher than physical measurements would have indicated. Despite this probability, it is considered that the correlation as such is established because of the careful and consistent approach to the data.

It will be recalled from the argument anticipating the correlation that the initial adverse gradient was viewed as an indicator of boundary-layer thickness both upstream and downstream of the laminar-separation bubble. An alternate form of the correlation, therefore, should emerge in a plot of U_P/U_∞ vs. θ_S/c. Such a plot is presented in figure 2. If attention is confined, again, to those points for which R_{θ_S} is greater than about 350, it is seen that higher peaks generally correlate with thinner laminar boundary layers near separation, and therefore, by inference, with thinner turbulent boundary layers downstream of the closed bubbles of separated flow.

The two points which most clearly do not correlate in the figures were chosen for the specific purpose of indicating that the correlation does not apply to sudden stalls attributable to bubble-bursting. The values of R_{θ_S} for these points were just less than 200. They are shown with flagged symbols to indicate that, although the stalls were almost certainly sudden, they did not meet the arbitrary requirement of $|\Delta c_l|_{stall} \geq 0.1$. When it is recalled that low values of R_{θ_S} correspond to relatively thin leading edges, this is not surprising; the typical pattern for such shapes is for nose stall to occur at a moderate lift coefficient, without any large loss of over-all lift, and with subsequent increases in lift with increasing angle of attack, up to $c_{l_{max}}$ (ref. 1). Accordingly, to find one or more clear cases of sudden stall for R_{θ_S} well below 350 or so, and therefore presumably clear cases of bubble-bursting, it was necessary to abandon the Δc_l requirement and rely on other indications.

The lift curve for the NACA 0010-34, a = 0.8 (mod.), $c_{l_i} = 0.2$, considered in conjunction with its leading-edge geometry, seemed to provide the clear indications desired. The curve and airfoil shape are reproduced in sketch (d), traced from reference 17. The pairs of data points indicating nose stall at positive and negative α are circled. To the scale of the plot, no nonlinearity of the curve is detectable for $|\alpha| <$ stall. Although



Sketch (d)

the increments $|\Delta\alpha|$ at stall were not more than 1°, stall was assumed at their midpoints, and stall c_l's were defined by extension of the linear range of the curve. The flagged points appearing on the figures correspond to the stalls so defined.

While additional quite clear cases of nose stall for low R_{θ_S} could have been found, it was deemed sufficient to present these two as illustrative.

It remains to examine whether the demonstrated correlation of figures 1 and 2, for sufficiently high R_{θ_S}, can be rationally reconciled with the bubble-bursting mechanism. It would seem that it cannot. In accordance with the discussion of bubble-bursting already given, both steep adverse gradients and thin laminar boundary layers at separation (corresponding generally to low values of R_{θ_S}, since $R_{\theta_S} = (\theta_S/c)R_c(U_S/U_\infty)$) should tend to promote nose stall. Similarly, shallow gradients and thick laminar boundary layers should tend to delay nose stall. Therefore, if anything, a correlation of increasing U_P/U_∞ with increasing Δs_l, or increasing θ_S/c, would be expected, rather than the correlation shown.

On the assumptions that (1) all sudden stalls are nose stalls, and (2) a laminar-separation bubble always exists on an unstalled, highly loaded leading edge, it is considered that the correlation that has been presented constitutes strong evidence for the common occurrence of nose stall by the reseparation mechanism. Furthermore, the analysis has indicated the essential validity of the Tani-Owen criterion for transitional reattachment, in the sense that such reattachment will always occur when $R(\delta)_S$ is above some critical value dependent upon the particular test conditions.

CONCLUDING REMARKS

An analysis has been presented which has indicated three things:

1. There appear to be two mechanisms of nose stall in low-speed two-dimensional flow; it is presumed that these are the mechanisms of bubble-bursting and reseparation which have both been described previously in the literature.

2. The Tani-Owen criterion for transitional reattachment of a separated laminar boundary layer appears to be essentially valid, and affords a means for distinguishing between the two mechanisms of nose stall.

3. For nose stalls by the reseparation mechanism, under a given set of test conditions, a correlation can be expected between high velocity peaks at stall and either steep initial adverse gradients or thin boundary layers in the region of these gradients.

Ames Research Center
National Aeronautics and Space Administration
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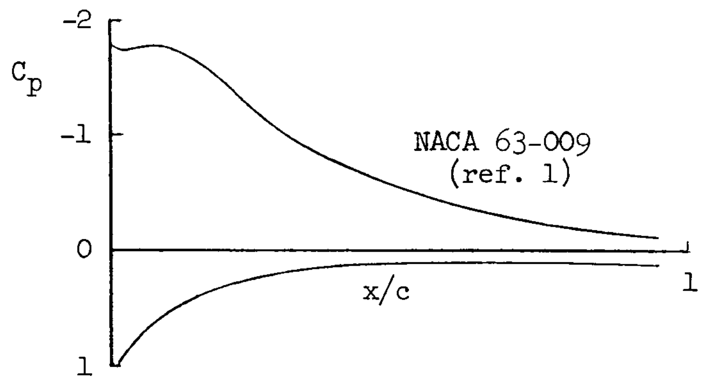
APPENDIX

REVIEW OF EXPERIMENTAL EVIDENCE FOR THE TWO HYPOTHETICAL MECHANISMS OF NOSE STALL

Evidence for Bubble-Bursting

Although this mechanism of nose stall seems intuitively the more plausible, the evidence in support of it is meager. It is primarily an inference drawn from the type of stalled pressure distribution frequently observed, and exemplified by sketch (e) - a distribution showing little



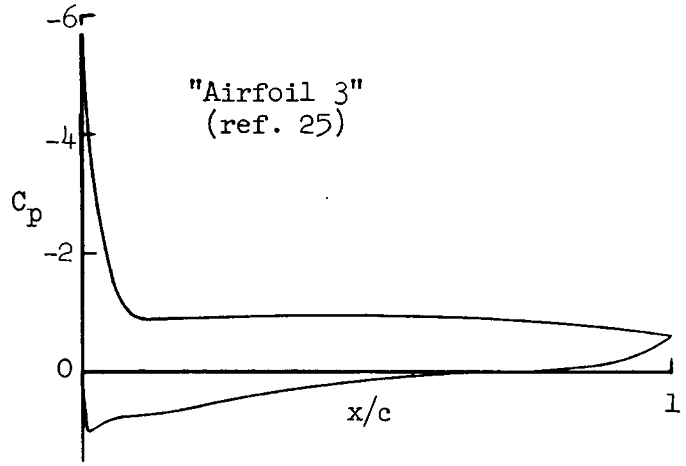
Sketch (e)

or no pressure rise as the flow approaches the point of separation. In the absence of such a pressure rise, it is reasonable to assume that the separating boundary layer is laminar, a conclusion supported by boundary-layer calculations based on such measured pressure distributions (e.g., see Crabtree, ref. 8). Since laminar separation existed both before and after the stall, it is natural enough to suppose that the stall was due to a sudden increase in the extent of the separated flow. As noted in the main text, a plausible physical argument for this mechanism has been advanced by Crabtree (refs. 8 and 10).

An additional bit of evidence in support of the bubble-bursting mechanism is more appropriately cited in the next section.

Evidence for Reseparation

Ocassionally, pressure distributions following nose stall have been measured in which there is a substantial pressure rise to separation. An example, in which the rise is so great as to clearly indicate turbulent separation, is shown in sketch (f).



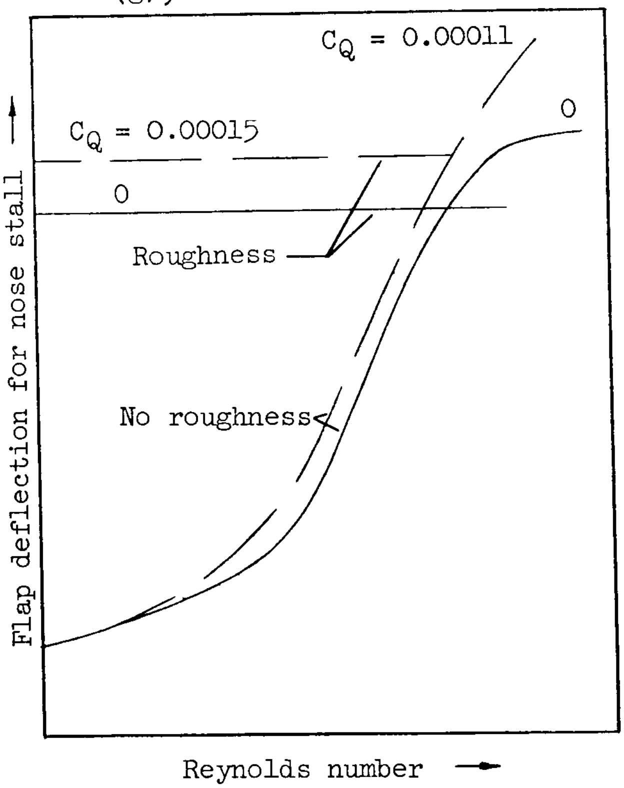
Sketch (f)

The primary evidence, however, comes from more specific studies. Prior to Wallis' suggestion in reference 2 that reseparation was the usual mechanism of nose stall, studies strongly indicating the mechanism were reported by Hurley and Ward for a model with an artificially disturbed boundary layer (ref. 9). (Disturbances were introduced between the points of stagnation and minimum pressure by means of either air jets issuing from spanwise rows of holes or by spanwise strips of roughness. The purpose was to hasten transition and suppress the laminar-separation bubble. Aerodynamic loading of the leading edge was varied by deflection of a trailing-edge flap. It was found that the bubble was reduced in size, but not eliminated, and that nose stall was delayed.) For a flow condition close to the stall, the boundary-layer shape parameter H varied from a relative minimum immediately behind the bubble, to a higher value a short distance downstream, to lower values again still farther downstream. The locally high values were of the order of magnitude generally regarded as indicative of incipient turbulent separation (refs. 26 and 27). From this observation, the authors concluded that nose stall had probably been initiated by reseparation in the region of high H values. Later, Hurley concluded that this was definitely the case (ref. 28).

It is important to note that, with the model smooth and the air jets off, the model again being close to stall, the variation of H downstream of the bubble was almost constant, and below the critical order of magnitude, through the same region where the locally high values had been measured. From this, the authors concluded that the nose stall of the clean model was due to bubble-bursting; this is the additional bit of evidence for bubble-bursting alluded to in the preceding section.

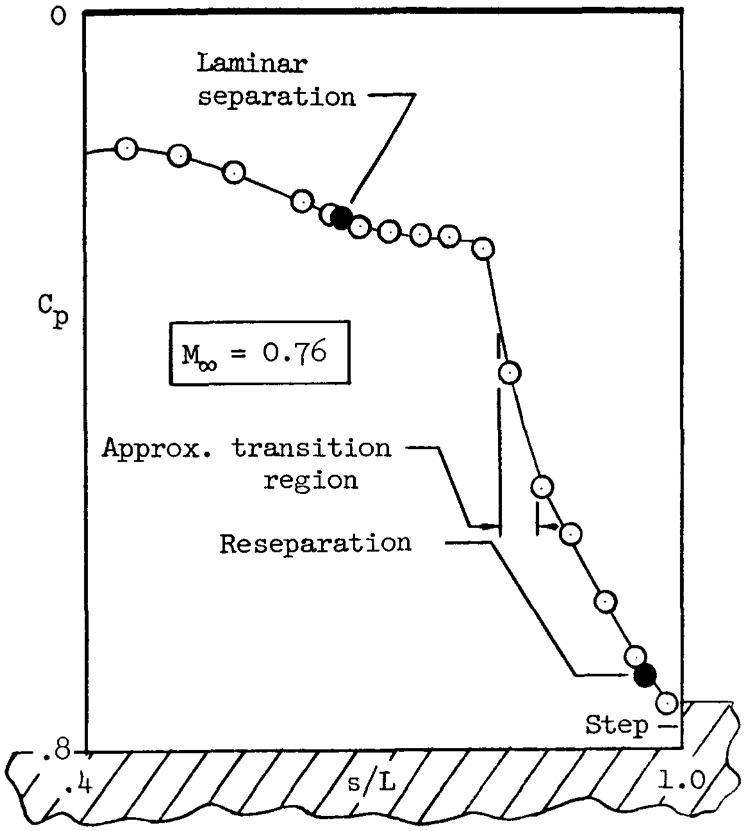
Wallis' suggestion that the reseparation mechanism should apply to clean airfoils was based on the argument that the effect of increasing Reynolds number should be similar to that of air jets. Thus, he suggested that the mechanism applies, "with the exception of low Reynolds numbers." Of interest in his report (ref. 2) is another stalled pressure distribution similar to that of sketch (f), obtained on a model with air jets operating. The pressure rise to separation was from $C_p \approx -8$ to $C_p \approx -3$.

Further work with the model used by Hurley and Ward has been reported in references 29 and 30. Of particular interest is the latter, in which Hurley and Ruglen report a study of the effect of suction through porous strips in the surface downstream of the bubble but upstream of the suspected point of reseparation. Conclusions were based on results obtained with a particular location of suction and small suction quantity which had no measurable effect on the pressure distribution through the region of the bubble; this was taken to mean that the sink effect on the bubble flow was negligible, so that the suction could not delay bubble-bursting. Results of tests through a range of Reynolds numbers are indicated in sketch (g), both for the clean model and for the model with one of the original roughness arrangements of reference 9, for which locally high H values had been measured. The delay in the stall at the highest Reynolds numbers for the clean airfoil (no roughness), and the delay at all test Reynolds numbers for the airfoil with roughness, were taken to be clear indications of reseparation stall. The relatively small delay for the clean airfoil between the lowest and highest Reynolds numbers may also indicate reseparation stall, or may indicate an undetected effect of the suction on the bubble flow.



Sketch (g)

An entirely different case of reseparation of a boundary layer a short distance downstream of a laminar-separation bubble is provided by Chapman, Kuehn, and Larson in their study of separated flows (ref. 4). Such double separations were observed in a number of cases of subsonic flow over steps. The pressure distribution for the case which they illustrate is reproduced here in sketch (h). The abscissa is fractional distance



Sketch (h)

from a sharp leading edge, along a flat surface, to the step. Since the model was at a negative angle of attack, a stagnation point presumably existed on the flat surface itself, so that the flow was not disturbed in any way by the sharp leading edge. The free-stream Mach number was of the same order as the peak Mach number near the leading edge of an airfoil at high lift in a low-speed stream. While the point of reattachment following laminar separation was not determined, it was presumably close to the transition region; in fact, the authors cite the association of an abrupt pressure rise with transition as evidence that transition is occurring closer to reattachment than to separation. In all respects, then (except curvature of the surface), the flow seems strikingly similar to that about the leading edge of an airfoil with a laminar-separation bubble.

The great variety of possible separated flows is much discussed by Chapman, et al. It is appropriate to keep in mind, therefore, that the present state of knowledge restricts any discussion of airfoil stall to particular separated flows. These recognized flows very likely do not exhaust the possibilities. In this connection, it is interesting to note the observation by Wallis and Ruglen (ref. 29) that a laminar-separation bubble on an airfoil nose can be followed, downstream, by a turbulent-separation bubble of such small extent that the nose can in no way be considered stalled. In their case, the turbulent separation was induced by a surface wire. It is perhaps also appropriate to point out that mechanisms of nose stall essentially equivalent to those discussed here could occur in the absence of a laminar-separation bubble. The equivalent of bubble-bursting would be simply the failure of the bubble to form following the first appearance of laminar separation. The equivalent of reseparation would be the sudden onset of separated flow a short distance downstream of transition in a fully attached boundary layer. In fact, it would seem that these mechanisms almost certainly do occur at sufficiently low, and sufficiently high, Reynolds numbers, respectively.

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TABLE I.- SELECTION OF AIRFOILS EXHIBITING SUDDEN STALL AT $R_c = 6\times10^6$

NACA airfoil	α_{stall}	$\frac{U_p}{U_\infty}$	Δs_l	$\frac{\theta_s}{c} \times 10^5$	R_{θ_s}	Reference
2-006	-	3.61	0.44	1.76	358	19
3-006	-	3.64	.33	1.61	330	20
1408	+	4.14	.24	1.45	338	12
	-	3.76	.29	1.42	301	
0009	-	3.82	.35	1.60	346	12
0012	+	3.55	.66	2.26	452	18
	-	3.71	.63	2.21	462	
1412	+	3.41	.75	2.31	444	12
2415	+	3.00	1.37	3.14	530	12
	-	3.13	.98	3.02	534	
23012	+	3.56	.89	2.34	469	18
	-	3.62	.51	2.07	422	
23015	+	2.99	2.02	3.57	601	18
[a]23021	+	2.43	5.55	6.48	887	12
	-	2.62	--	4.38	647	
[b]0010-34, a = 0.8 (mod.), $c_{l_i} = 0.2$	+	3.54	.12	.97	193	17
	-	3.68	.11	.96	199	
0012-64, a = 0.8 (mod.), $c_{l_i} = 0.2$	+	3.56	.56	2.29	460	17
63-009	+	3.82	.22	1.44	311	12
	-	3.65	.22	1.37	282	
63-209	+	4.24	.25	1.30	309	14
	-	4.12	.18	1.17	272	
63_1-412	-	3.71	.28	1.61	336	12
64-208	+	3.94	.22	1.18	263	12
64A010	+	3.75	.29	1.49	316	13
	-	3.88	.28	1.46	319	
64A410	+	4.34	.28	1.46	358	13
	-	3.46	.20	1.44	281	
64_1-012	+	4.02	.43	1.73	393	18
64_1-212	-	3.85	.31	1.62	353	12
64_1A212	+	3.98	.36	1.77	397	18
64_1-412	+	4.08	.34	1.64	378	18
	-	3.89	.34	1.65	361	
$65_{(112)}$A111 (approx.)	+	3.96	.21	1.52	340	16
	-	3.58	.32	1.64	332	
65_1-412	+	4.02	.38	1.67	379	12
	-	3.44	.16	1.62	314	
66_1-212	+	3.94	.38	1.69	376	12
	-	3.85	.25	1.58	343	
66(215)-216, a = 0.6	+	4.04	.49	2.18	496	12
	-	3.80	.55	2.07	444	
66(215)-316, $\left\{\begin{matrix} a = 0.6, & c_{l_i} = -1.2 \\ a = 1.0, & c_{l_i} = 1.5 \end{matrix}\right\}$	+	3.73	.61	2.18	460	15
	-	3.77	.66	2.22	472	

[a]Stall at negative α not used for figure 1 because scatter in computed velocity distribution did not permit adequate definition of Δs_l.
[b]$|\Delta c_l|_{stall} < 0.1$

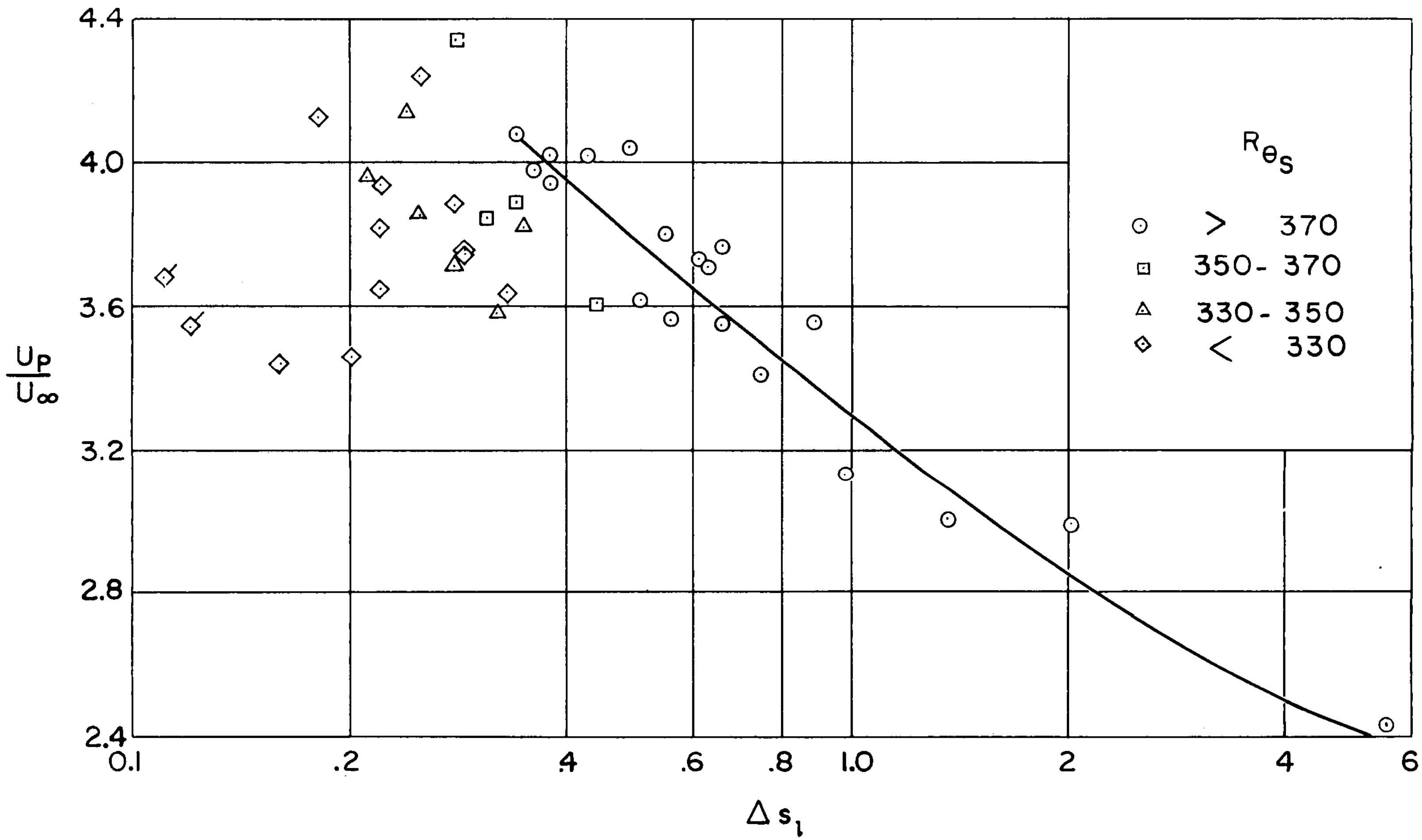

Figure 1.- A correlation of peak velocity ratio at stall with initial adverse gradient as indicated by the adverse run Δs_l.

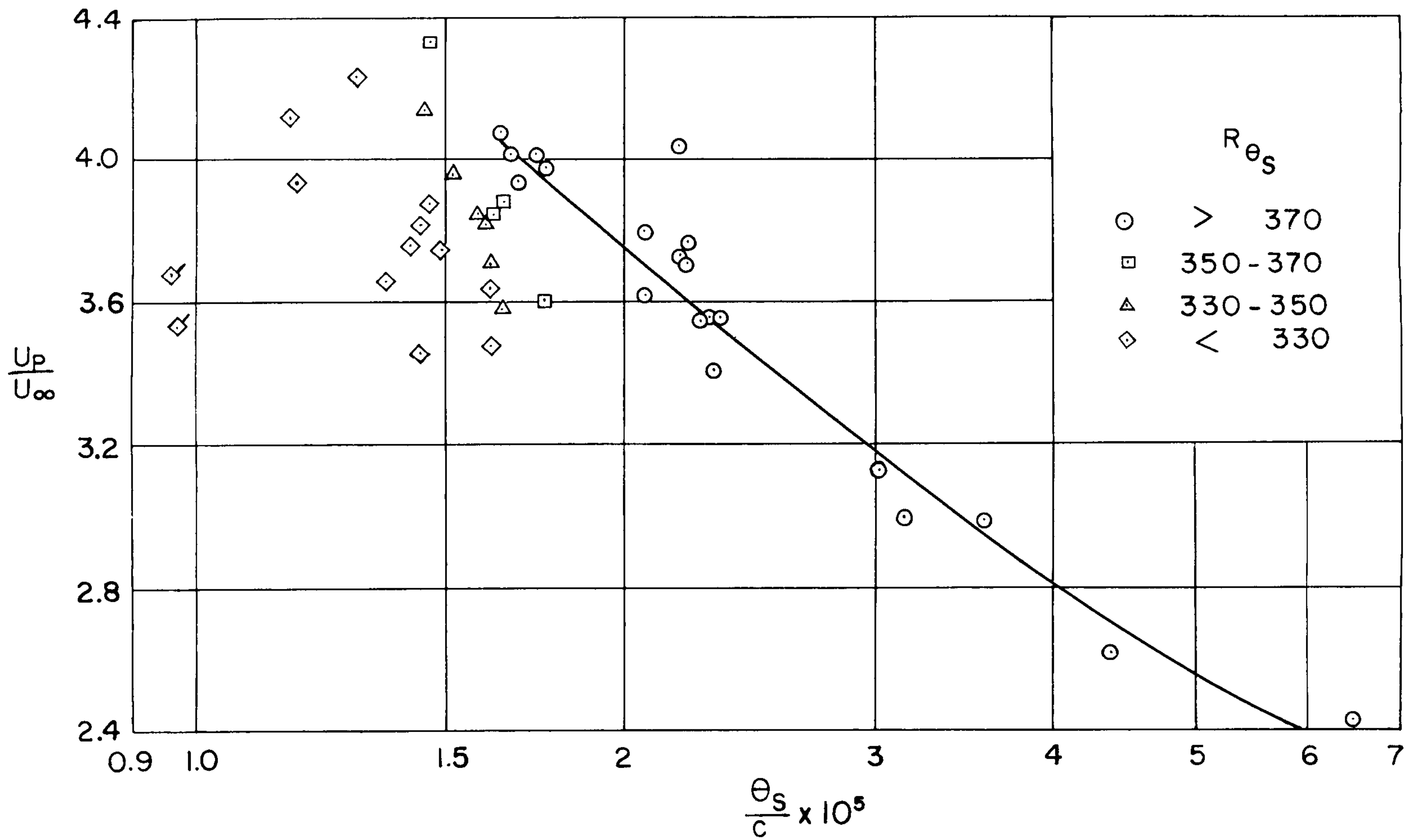

Figure 2.- A correlation of peak velocity ratio at stall with boundary-layer momentum thickness at laminar separation.